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UNITED STATES NAVAL POSTGRADUATE SCHOOL

THESIS

A COST-EFFECTIVENESS METHODOLOGY

FOR

ARTILLERY WEAPONS SYSTEMS

by

Myrl W. Allinder, Jr.

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A COST-EFFECTIVENESS METHODOLOGY FOR ARTILLERY WEAPONS SYSTEMS

by

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ABSTRACT

The composition of an artillery system and its mission in a non-nuclear environment is discussed. Four scenarios are defined in which the artillery system must perform its mission, and the tasks are detailed.

A concept for a measure of effectiveness (MOE) for artillery is developed and a methodology is presented. The effects of the scenarios on the MOE are analyzed and the constraints are discussed. A mobility concept is developed and a definition is presented.

Costing concepts and techniques are presented with notation developed for computer application to the artillery system costing problem. Some cost estimating relationships (CER's) are suggested.

A cost-effectiveness analysis is made employing the developed MOE and costing procedure. Some decision criteria are stated and discussed.

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I INTRODUCTION

1.1 DEVELOPMENT OF ARTILLERY

The standard U.S. artillery weapons in September 1945 consisted of seven towed howitzers, two towed guns, three self-propelled (SP) howitzers, one self-propelled gun, one self-propelled mortar, one heavy mortar, two rocket weapons, and three high speed tractors. Today the U.S. Army has nine Standard A field artillery weapons, excluding antiaircraft guns and artillery guided missile systems. If it were technologically feasible, there are advantages to reducing the length of the artillery weapons list even more. Fewer weapon types reduce the logistic loads and training requirements. However, no two or three artillery pieces have yet been designed to successfully fulfill all the roles called for in an artillery system.

Specifically, artillery must be a flexible, mobile system capable of varying increments of firepower against all the varying targets the supported infantry units are likely to encounter in an engagement. On the offensive, artillery must provide preparatory fires to soften an objective immediately prior to an assault. If on the defensive, artillery must provide final protective fire on all avenues of approach into friendly positions, and fire into friendly positions in the event of enemy penetration. Once the enemy attack has been blunted, artillery must be capable of pursuing the fleeing enemy by fire, and capable of providing high angle indirect fire against targets on reverse-slope terrain, i.e., hit targets on the far side of the mountain.

If enemy artillery fire is brought to bear against friendly positions, friendly artillery must provide immediate counter-battery fires to silence enemy guns. Lastly, artillery must provide interdiction and harrassing fires to disrupt enemy communications, supply, movement, and to reduce enemy morale.

Current heavy weapons designed for long range interdiction and counter-battery fires cannot elevate sufficiently nor fire rapidly enough for the short range, indirect, high volume of fire required against large concentrations of enemy troops in the immediate vicinity of the forward edge of the battle area (FEBA). Likewise, the 107mm mortar is useless against targets requiring the range or the penetrating power of the eight-inch projectile.

Table 1.1 ARTILLERY WEAPON TYPES, 1945 AND TODAY

	Total Number Types	Number (SP)	% (SP)	Number Calibers
US Armed Forces 1945	17	5	29	8
US Army (Standard A)	9	4	44	5
USMC	6	3	50	4

Excluding artillery guided missile systems, Table 1.1 reflects the trend toward the streamlined, highly mobile, partially helicopter-transportable infantry-supporting arms system. Airmobile artillery, amphibious artillery, and artillery capable of significant increases in rates of fire and ranges are current items of priority interest and development. [5, 13, 17, 23] Although field artillery fire control procedures remained unchanged for several decades, the introduction of new and better fire control equipment since WW II has improved coordination and effective delivery of artillery fire. Panoramic telescopes and other conventional aiming devices have been made more accurate and easier to operate. Radar and other electronic means are used whereby forward observers can more accurately determine range to the target. The space age is influencing artillery development by introducing new techniques for geographically locating weapons and targets in the field. Many other significant advances have been registered, one of the more important being the development of mobile electronic equipment to automatically compute fire orders. [14, 20]

The trends have been established. The artillery system of the future will likely be built around a few highly mobile, light-weight weapons capable of a rate of fire several times that of today. Automatic loading and computerized fire control systems will make it a more formidable supporting arm indeed.

1.2 ROLE OF ARTILLERY IN THE SUPPORTING ARMS SYSTEM

As the artillery system of the future is developed, it should be designed to be fully integrated with the other major supporting arms, naval gunfire and close air support. The complementary blending of these three systems will, to some extent, mold some of the features of each co-system. In a combat situation, comparative capabilities and limitations ought to be kept in mind when selecting the ordnance delivery means. This same principle applies to the development of any one of the three systems as well. If a new artillery system is being contemplated which can attack targets at ninety kilometers, naval gunfire and close air support should be considered as alternatives in any comparative analysis in order to arrive at a truly efficient supporting arms system.

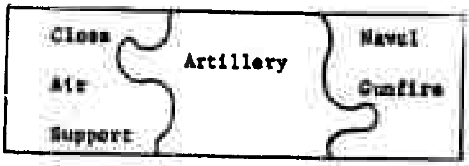

Figure 1.1 THE SUPPORTING ARMS SYSTEM

Since the artillery system is a component of the supporting arms system, care should be exercised that the capabilities of any other component are not unnecessarily duplicated.

1.3 THE ARTILLERY SYSTEM

What comprises an artillery subsystem, which shall be referred to as simply an artillery system? Figure 1.2 gives some indication. Not all of the components shown exist wholly for artillery, but a significant fractional value of the expended effort goes in support of artillery. For example, base facilities may house infantry, tank, and other units, but some proportion of expenditures of dollars for base maintenance and upkeep are directly or indirectly attributable to the presence of some or all of the artillery system components.

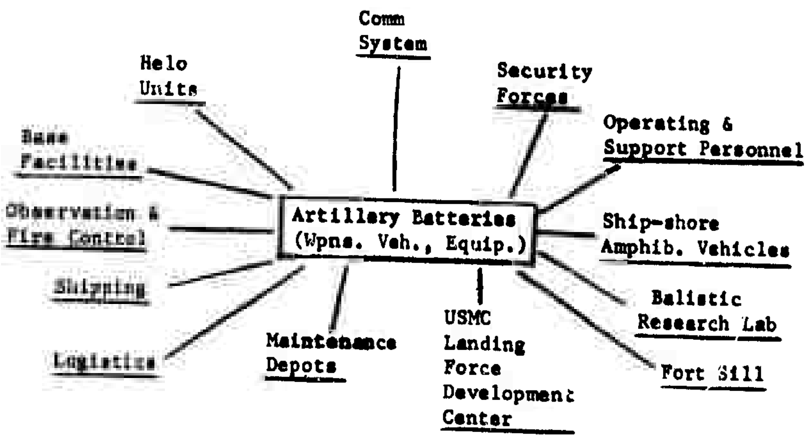

Figure 1.2 COMPONENTS OF AN ARTILLERY SYSTEM

At least two questions present themselves. What proportion of the supporting component effort actually goes in support of the artillery system, and how are the component subcomponents defined? If the second question is pursued to the end, the ultimate subcomponent of

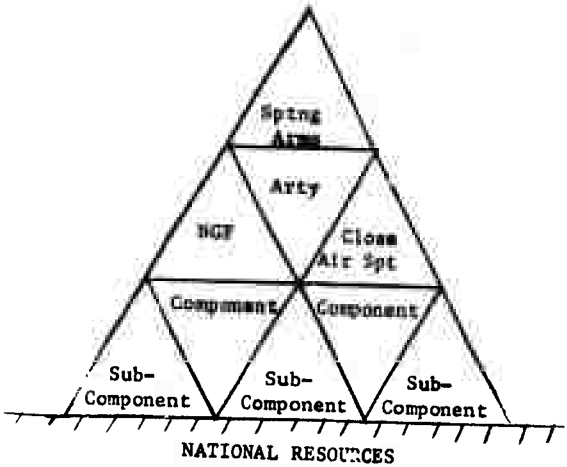

Figure 1.3 SYSTEMS AND SUPPORT COMPONENTS

all systems, as the figure above indicates, is the pool of national resources. For simplification, only components directly supporting the artillery units are usually considered. Costing of the support components and of the artillery units should be done as accurately as time, detail, and good judgment permit.

The answer to the first question may be available from historical sources, provided future requirements do not differ too greatly from past experience. Problems of unreliable estimation may be encountered if extrapolations are carried beyond the range of past data. For example, the number of required helicopter sorties per artillery unit per unit of time in the future may be approximated by careful analysis of the artillery unit's operations from past equal units of time.

However, if total numbers of artillery units are doubled, or the system is preparing to operate in an environment in which it has never operated before, of if an entirely new artillery system with different logistics and mobility requirements is about to be phased in, past operational requirements for helicopters in the old system may bear no or little relation to the new future requirements.

A skeletal example of a basic artillery system is the field artillery regiment of the Marine division. The artillery regiment is the primary source of fire support for the division and is currently composed of the basic elements shown in Figure 1.3 with specific support units omitted, such as external logistics support, helicopter support, medical support, Marine Observation Squadron support, etc.

1.4 CONCEPT AND SCOPE

The purpose of this paper is to develop a technique whereby the efficient, optimum selection of future alternative artillery systems is possible. As mentioned, an alternative artillery system is the sum total of all the specific numbers and types of equipment, weapons, and personnel which is proposed for implementation as the operational unit. A proposal utilizing only one type weapon would be an alternative. A system in which the 105mm howitzers were to be replaced by newer models of 105's is a different alternative. Yet another alternative would be a system which simply adds one more battery of a current type weapon to the system. Finally, the system in being is an alternative against which all proposed alternatives will be measured for effectiveness and cost.

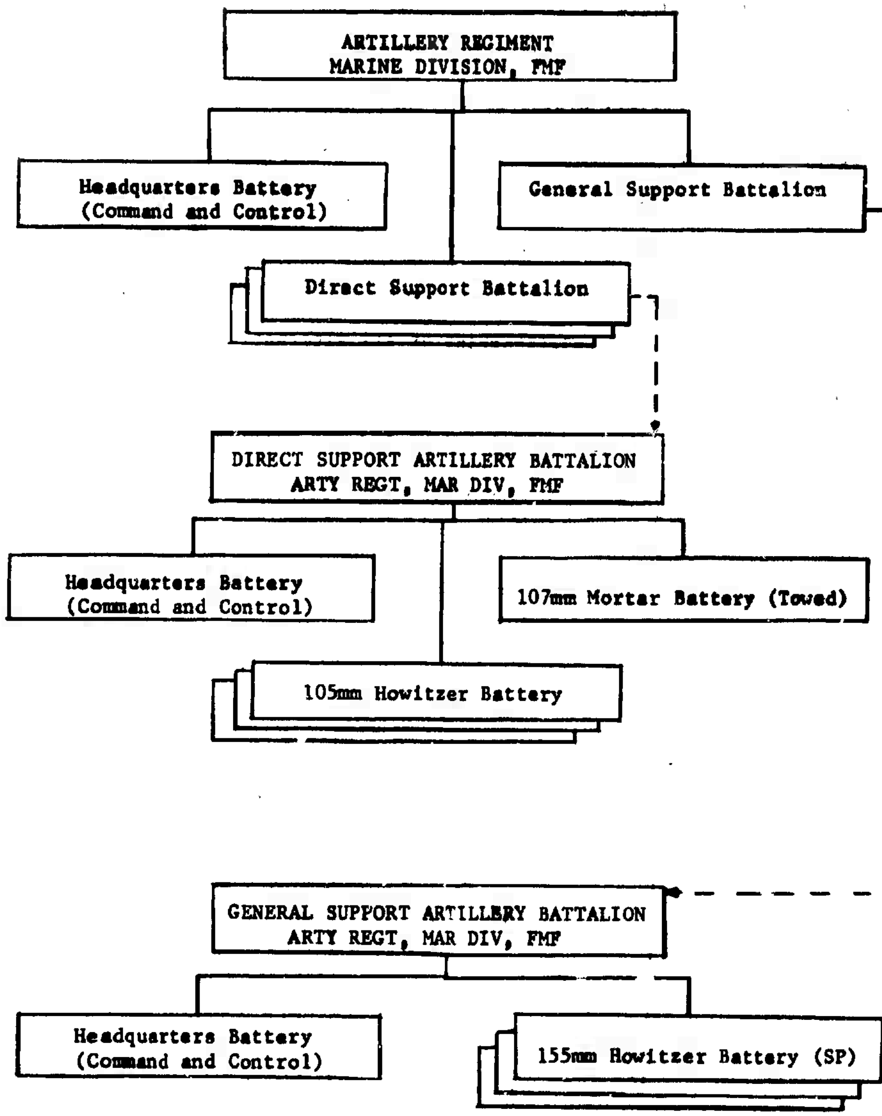

Figure 1.4 MARINE ARTILLERY REGIMENT

Once two or more alternatives are proposed, including the present system, an efficient and hopefully optimum[1] system can be chosen. An efficient artillery system is one which inflicts no fewer than a prescribed number of casualties against a given number of targets in the various scenarios, and inflicts those casualties at the expenditure of less national resources than any other feasible alternative. A feasible alternative is one which meets all the constraints. Figure 1.4 shows some relationships of six alternatives. The curve represents the frontier of maximum attainable numbers of casualties per engagement for a given budget. Of the six alternatives shown, alternatives three and four are infeasible since they do not meet the constraints. Alternatives six and two are feasible, and one and five are efficient at different budget levels. System five is optimum for the indicated minimum casualty level.

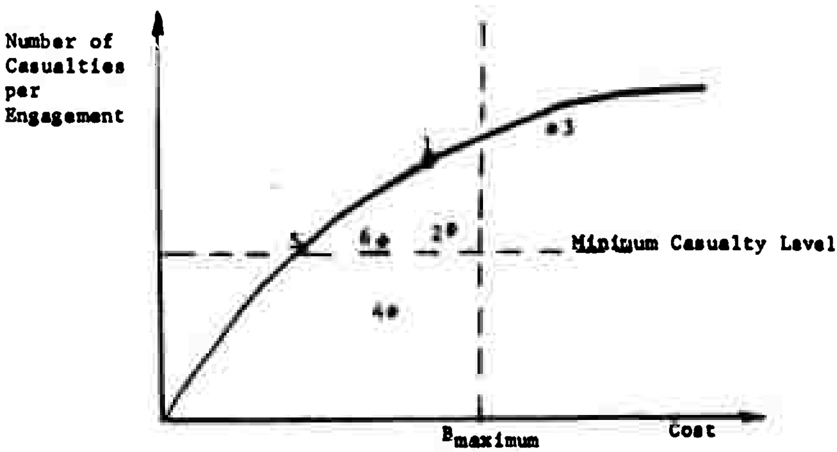

Figure 1.5 CASUALTIES PER ENGAGEMENT VS ALTERNATIVE SYSTEM COST

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[1]Not necessarily a unique optimum. Multi-optima may exist.

To accomplish the goal of selecting an optimum, efficient alternative it is necessary to restate the mission and tasks of artillery. The mission and tasks must be performed in varying geographical and climatological conditions which will be defined under the heading of Scenarios. Scenarios will have an influence not only on the effectiveness and costs of the artillery system in inflicting casualties, but will also affect operating and maintenance costs and attrition on the system.

It would be well to reduce the mission and task requirements to a measurable expression which will truly compare alternative systems and aid in selecting an optimum or efficient solution. This is the purpose of the statement of the criteria for this paper: Of the proposed alternatives which are able to inflict the minimum prescribed number of casualties against a defined target, select that system which has minimum non-engagement system cost and incurs minimum variable cost per casualty per engagement.

Finally, the cost data and effectiveness data of the alternatives must be compared and evaluated for a unique optimum solution if one exists. Otherwise, trade-offs among equally efficient alternatives will be compared and a solution obtained based on some additional decision criteria.

In attacking the problem of finding a procedure for selecting the efficient artillery system, two simplifying assumptions or reductions of the problem have been made. Only the artillery system is considered, and the interplay of naval gunfire and close air support with artillery have been excluded. Secondly, the scenarios put aside artillery's nuclear capability and its implications of central war and thus consider only conventional ordnance.

1.5 SUMMARY OF CONCLUSIONS

The evolving artillery system of the future will be a sophisticated, highly mobile, and computer-assisted array built around fewer weapon types. The method of minimizing expected variable cost per casualty and non-engagement system cost, while meeting minimum mobility and casualty constraints, will select the desired alternative. Detailed costing matrices of present battery types will be required in developing cost estimating relationships as aids in designing and estimating costs of future weapons.

1.6 PLAN OF THE STUDY

The problem addressed by this paper is: Define a measure of effectiveness and construct a cost-effectiveness model for evaluating and selecting from among future artillery alternatives.

The plan of this study is first to describe the job that is required to be done, or mission of artillery, and the environments in which this job may reasonably be expected to be accomplished. From there this paper will discuss effectiveness for an artillery system and how to measure it, including the effects of the scenarios on the artillery system, and will present a measure of effectiveness to secure an efficient system. Next will be discussed the costing problem, costing matrices for present artillery battery types, and the development of cost estimating relationships. Finally, cost and effectiveness will be compared for the selection of the optimum alternative. Included will be a discussion of alternative decision criteria to be utilized in the event of multi-optima alternatives to the artillery problem.

II MISSION AND SCENARIOS

2.1 DISCUSSION

Mission. The primary artillery system mission is to "provide close and continuous support to ground forces by neutralizing or destroying those targets which constitute the most serious threat to the supported unit". [3] Such support includes counterbattery fire, attack of enemy reserves, restricting enemy movement, disrupting enemy command systems and the destruction of other enemy installations. To compare alternative systems for this mission it is necessary to further specify the particular surroundings or environment in which the system may likely operate. The specified area may impose additional equipment or support requirements on the system, and consideration of it lends to a more realistic evaluation of the system.

Scenarios. This environment in which the system must operate and in which it is desirable to evaluate the system is called the scenario. Consideration of the system operating in various scenarios is an attempt to compensate for the uncertainty of the exact location in which future artillery system operations are likely to occur. Figure 2.1 is a representation of the specified mission and the set of environments or scenarios in which the mission may be performed. Two primary reasons come to mind for examining the system in the light of a particular scenario. One is to determine the physical effects of the environment on the operation and maintenance of the system. The second is to determine the effects of the environment on hitting targets and causing casualties.

MISSION

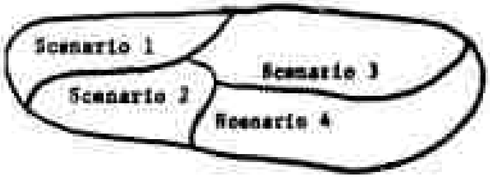

Figure 2.1

Some of the scenario characteristics which cause physical effects on the system are temperature, humidity, dust, and sand. They affect the life expectancy, attrition, operating costs, and maintenance cycles of the system. Producing casualties on the target will be affected by the ability of the target and the artillery system to move in the scenario, the ability to accurately locate on the ground both the artillery weapons and the target, and the ability to see the target to adjust fire on it. The presence and amount of land and/or vegetation mask must be considered since it will limit, somewhat, the types of artillery weapons which will have the ability to fire on the target.

Four scenarios are used in this paper. These are labelled the ideal, the rain forest, the desert, and the mountain scenarios. The next usual development in a cost-effectiveness study is to detail the scenario. Here such detail would prescribe exactly the temperature, humidity, soil types, vegetation types and coverages, seasonal variations, vegetation heights, elevation of terrain, slope of terrain, etc. However, the task is sufficient for at least part of another report, and only the general characteristics are presented here.

The general characteristics are enough for the moment to determine the effects of these scenarios on the performance of the artillery system.

Tasks. Within each scenario are a set of tasks which must be performed by the system to accomplish its mission. Task is here defined as the type of target on which the system must inflict casualties. A casualty is any enemy target rendered incapable of performing its combat function. Figure 2.2 represents the tasks within each scenario.

SCENARIO

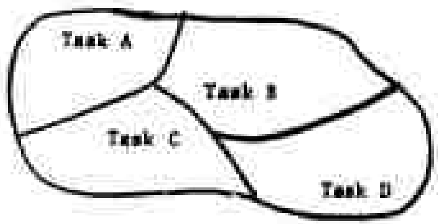

Figure 2.2

Tasks are generally distinguished by personnel or non-personnel targets and by hardness of target. Hardness corresponds to the effective casualty producing radius of a particular bursting projectile against a particular target. Each projectile will have a larger casualty producing radius against soft targets, and smaller radii against harder targets. For example, consider Table 2.1.

Table 2.1 HYPOTHETICAL PROJECTILE EFFECTIVENESS VS VARIOUS TARGETS

Types of Targets	Casualty Producing Radius of A Hypothetical Projectile (Meters)
Personnel	
Open, standing	25
Prone	18
Foxhole	10
Semi-hard	
Materiel	10
Trucks	8
Buildings	8
Hard	
Tanks, armored vehicles	2
Pill boxes, reinforced positions	2
Counterbattery	10

This hypothetical round could produce casualties against troops in foxholes at 10 meters or less from the burst point and could damage certain buildings 8 meters from the burst point. Particular targets will often be mixed, troops will be defending from within fortified positions or moving about in armored carriers. For this reason it is convenient to reduce all tanks, crew served weapons, and emplacements to their personnel equivalents. For example, consider the above hypothetical projectile against an enemy tank with a crew of four.

The target would be considered as one personnel target of four persons, and a casualty producing radius of two meters would be used to compute the expected number of rounds required to inflict a certain percentage of personnel casualties.

2.2 SCENARIOS

Rain Forest. There are three principal rain forest areas in the world: the African, the American, and the Indo-Malayan. These rain forests comprise nearly one fourth of the continental land area. The vegetation of these areas is dominated by tall growths of hardwood trees, which in turn influence communications, observation, movement, and the accurate mapping of the areas. These areas are characterized by an annual average rainfall of over eighty inches, tree canopies averaging over 150 feet high, and a variety of undergrowth ranging from none in the virgin rain forest areas to veritable tangles of impassable vines and brush in areas that have been cut over and then allowed to lie fallow. [11, 26]

Each task in such an area will involve locating and fixing the target, adjusting fire and compensating for the canopy, and moving to new firing positions.

Desert. Desert areas of the world are designated primarily on the basis of their average annual rainfalls.[1] Typically, the twelve desert regions of the world average less than six inches of rainfall per year,

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[1]Average rainfalls can be misleading. The hamlet of Dakhla in the Sahara once went eleven years without a trace of rainfall, and yet Dakhla has an average rainfall of five inches per year. [12]

with much of the Sahara averaging less than one inch of rain per year.

Along with sparse rainfall, the one-seventh of the land surface which is desert is characterized by high temperatures. The low humidity of the air lets the sun's rays penetrate the atmosphere and heat the ground to an extent impossible in moister climes. Daytime summer temperatures of 120° F are commonplace with the ground temperatures often 30-50° above that. Night temperatures will plummet 50° or more below the daytime high, again due to the lack of humidity. Visibility is often limited by heat mirages and severe dust and sand storms which reduce visibility for days. Movement is usually unrestricted by obstacles and barriers except during the sandstorms and the infrequent rain showers. [12, 26, 28]

Mountains. Mountain areas are vaguely described in various reference texts when it comes to defining the difference between a mountain and a hill. Generally, mountain regions are given as those where land masses rise more than three thousand feet above sea level. Important to the artillery system in the discussion of this scenario is not only the total height of the mountains above sea level, but also the slope or rate of gain in elevation of the land mass.

The general areas of the mountain regions of the world comprise some 25% of the continental land area. Mountain areas are usually typified by channelized routes of communications, large variations in elevation within short horizontal distances, and meteorological conditions which change rapidly and often unpredictably. Average slopes usually exceed 30%, but include all the extremes that go to make up an average. Vegetation may vary from rain forest in the lower elevations to only lichens and moss above the timber line which occurs around 12,000 feet above sea level. The run-off after a plentiful rainfall is often heavy, and small streams may easily flood as a result.

At higher elevations, such as Tibet where the average elevation of the entire country is over 15,000 feet, atmospheric pressure is reduced, temperatures vary over a wider range and weather is even more unpredictable than in mountains of lower absolute heights. Unusually low temperatures come on with nightfall, and winters are characterized by extremely low temperatures with snowfall in varying areas in amounts according to humidity. [11, 30, 31]

Ideal. The ideal scenario considered here is a non-existent perfectly mapped, flat, table-land which has invariable weather conditions of standard temperature and humidity every day, no wind, unlimited visibility, and a few low hills from behind which the artillery pieces are unobservable by the enemy. There are no trees, other vegetation, or land masses to mask friendly artillery fire or to afford cover and concealment to the enemy targets. The region is trafficable and communications are perfect.

Combinations. Taking rainfall, terrain slope, and temperature as a basis for a three-dimensional scenario space, every possible target location on any continent may be described in terms of the above quantities. Many locations reduce to linear combinations of temperature, rainfall, and slope. Rainfall and temperature combinations imply the vegetation that accompany them, i.e., vegetation heights, types, and amounts are direct functions of the temperature and rainfall. As an example, consider the mountainous rain forest of northwestern South Vietnam. This might be represented as in Figure 2.4. This figure is an obvious oversimplification of a complex terrain and climatic condition, and it is perhaps a gross assumption to consider that temperature, rainfall, and slope are simple orthogonal vectors which may be added by vector addition. Yet, there may be value in appraising the effects of a combination of the quantities in this way. All possible effects on the artillery system may be considered and account taken of the total computational errors which may be introduced into the system as the result of operating in such a complex environment.

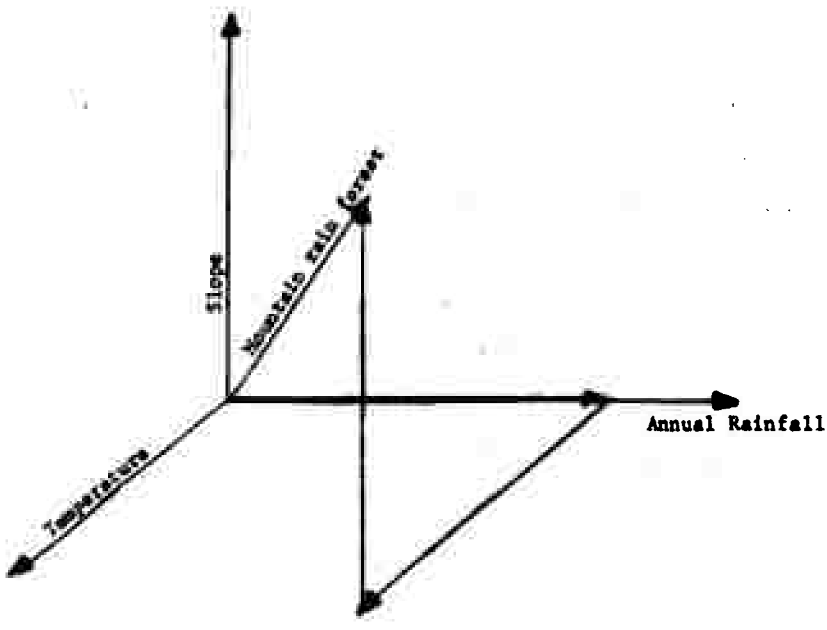


Figure 2.3 VECTOR REPRESENTATION OF SCENARIO PARAMETERS

III A MEASURE OF EFFECTIVENESS

3.1 DISCUSSION

Developing a measure of effectiveness (MOE) which, along with cost considerations, will accurately order alternatives so that the most desirable one may be selected is a difficult problem that has no unique solution in many cases. Three independent studies of the same problem could possibly produce three independent measures of effectiveness, each of which would be valid and each might even rank all the alternatives in the same order, though not necessarily so. Defining an MOE before fully understanding the mission, the scenarios, and the basic system alternatives may lead to a precise measurement of a wrong or poor performance parameter with a resultant ranking of alternatives according to the wrong or poor criteria.

This chapter will attempt to carefully define a measure of effectiveness (MOE) for ranking proposed alternative artillery systems by first discussing what effectiveness is for an artillery system. Next, a mathematical model will be presented in the form of an objective function to be minimized. The parameters of the artillery system's performance will be presented and then analyzed under the effects of the scenarios previously discussed. Finally, the constraints to the objective function will be presented, defined, and discussed.

What is effectiveness and how can it be measured? For a mechanical engineer effectiveness might be the measure of the amount of work obtained from an internal combustion engine. This effectiveness is a function of the total energy producing fuel that was burned and the efficiency of the motor. Effectiveness for a financial investor might be simply the cash flow from his investments.

In a similar manner, in the process of choosing an alternative artillery system, the MOE will be a measure of some output being realized for the investment in that particular alternative. It is at this point that the investment picture becomes clouded for artillery systems. What is the 'output'? It obviously isn't dollars, unless enemy targets destroyed is somehow converted to dollars. How much output or return is enough or satisfactory? How is the return best measured, or can it be measured at all? What is the exact amount of investment required in the artillery system to get enough return? If the expected types and expected numbers of each target are held fixed for each engagement in each scenario, and for a given fixed fraction of casualties per engagement for each scenario, some conditions may be stated that will define a return on an artillery investment:

Minimize: The vector whose components are Variable costs per engagement and Artillery non-engagement system cost

Subject to: Future budget constraints are not exceeded
Casualties inflicted/engagement = that required
Number of targets/engagement = that specified

The simplifying assumptions of fixed types and numbers of targets per engagement is really the product of two foregoing assumptions. First, that all expected engagements in which artillery would logically be employed will fall within minimum and maximum bounds for numbers and types of targets. Obviously, the employment of artillery against one lone enemy soldier might be questionable. In like manner, the enemy is assumed to possess clear judgment, and would never mass or concentrate his forces beyond the limits of tactical efficiency into a formation such as a phalanx of one hundred men wide by one hundred men deep. The second assumption is that each artillery alternative examined will satisfy the constraints of the problem, i.e., that each alternative will perform equally well within the minimum and maximum bounds for the numbers and types of targets per engagement.

Examining the criteria and the constraints stated above, it might be well to discuss the terms briefly at this point, and in more detail later. Minimizing variable costs per engagement means reducing all costs resulting from one combat engagement to the lowest figure possible. Variable costs per engagement will include the costs of replacing or repairing combat attrited weapons, equipment, and men, and the cost of the projectiles expended against the enemy. One disadvantage of this measure is that it will vary as a function of the number of engagements fought and the frequency at which the engagements occur. However, peacetime readiness costs will be minimized, and if the assumption is made that the number and frequency of engagements will affect all alternatives approximately the same as far as variable costs per engagement go, then this criteria will still be accurate and reliable in selecting an optimum alternative.

The artillery non-engagement system cost is the second component of the measure of effectiveness (MOE) and is simply the total cost of the alternative over its life less all variable costs incurred in combat. Included in the system non-engagement cost are such items as RDT&E, initial procurement, and readiness operations and maintenance costs for the life of the system.

The constraints set the bounds within which the alternatives must lie. The non-engagement system cost obviously must be less than or equal to the planned future budget. Costs do not normally occur at one instant in time, but are spread over the lifetime of the system. The system cost, then, will be a stream over time, and the planned budget will likewise be an estimated budget stream over the corresponding time interval. The next two constraints embody the assumptions stated at the first of this section. The number of targets per engagement will be as specified, and the alternative system must be capable of inflicting at least the required numbers of casualties per engagement.

A plot of non-engagement system cost vs number of casualties achieved in a specified engagement for various proposed alternatives might resemble the graph of Figure 3.1 This illustration

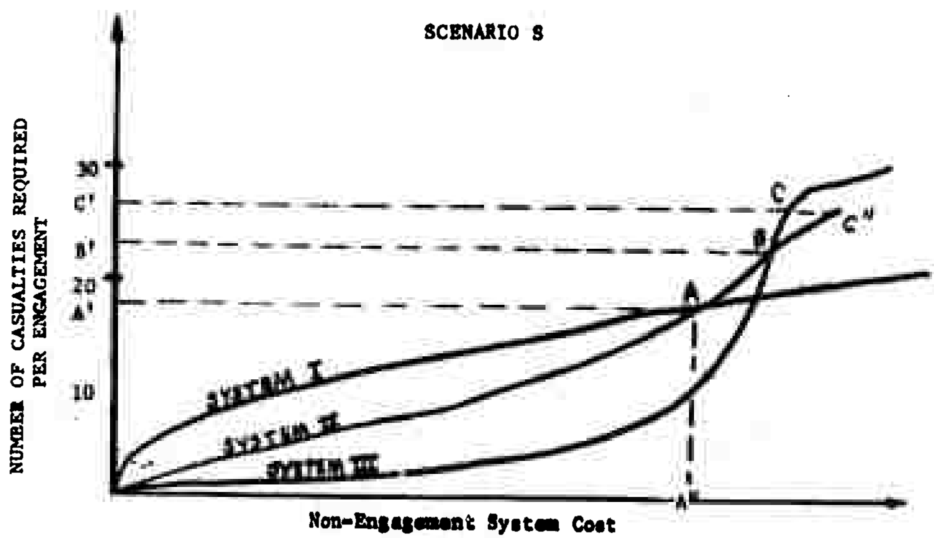


Figure 3.1 COST OF THREE ALTERNATIVES FOR GIVEN CASUALTY LEVELS

represents system cost in a particular scenario S, and for this instance system I will have the minimum non-engagement system cost if the number of casualties per engagement is less than A'. If the required number of casualties per engagement is between A' and B', then system II is the proper choice for this three alternative example. For any casualty rate above B', say C', then system III minimizes the non-engagement system cost required to achieve the desired number of casualties per engagement. The assumption is that each alternative can achieve an incremental increase in casualties for some incremental increase in system cost, excluding variable costs.

Figure 3.1 is the plot of three discrete artillery alternatives. Theoretically, several other discrete alternatives may exist with non-engagement system cost vs number of casualties per engagement plots as shown in Figure 3.2. As sufficient alternatives are considered and plotted, a composite curve, say V, emerges as a continuous boundary or frontier of efficient alternative solutions to the problem. For example, if A' casualties per engagement are required, A" is the minimum non-engagement system cost to achieve A' casualties, and A" must be spent on alternative IV.

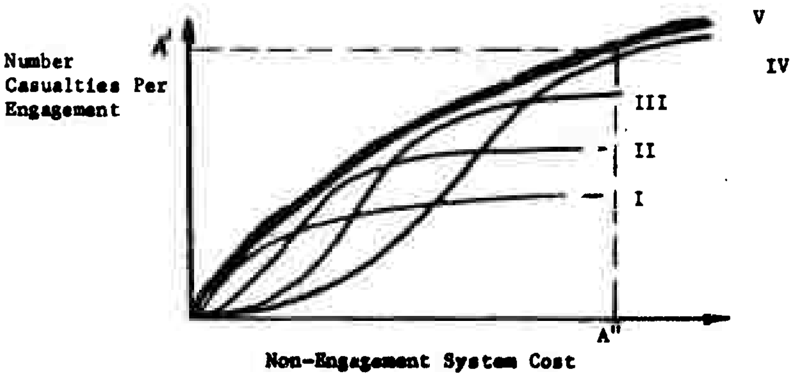


Figure 3.2 EFFICIENCY FRONTIER FOR NON-ENGAGEMENT SYSTEM COST

How do the two quantities, variable cost per casualty and non-engagement system cost, vary for a given number of casualties inflicted per engagement? An intuitive argument is presented via Figure 3.3. Consider a third axis coming out of the paper representing casualty level per engagement, then the curve in Figure 3.3 represents a plateau at some casualty level in a particular scenario, such as rain forest. The system which has minimum non-engagement system cost Y_1 has some variable cost C_1. Perhaps another alternative which has heavier weapons of greater caliber has non-engagement system cost Y_2, but its heavier projectiles are more efficient in the high canopied rain forest with a resulting variable cost C_2 less than C_1. As the non-engagement system cost increases to the right, the cost of replacing attrited equipment lost in the engagement will become the overriding factor and turn the variable cost per casualty upward again.

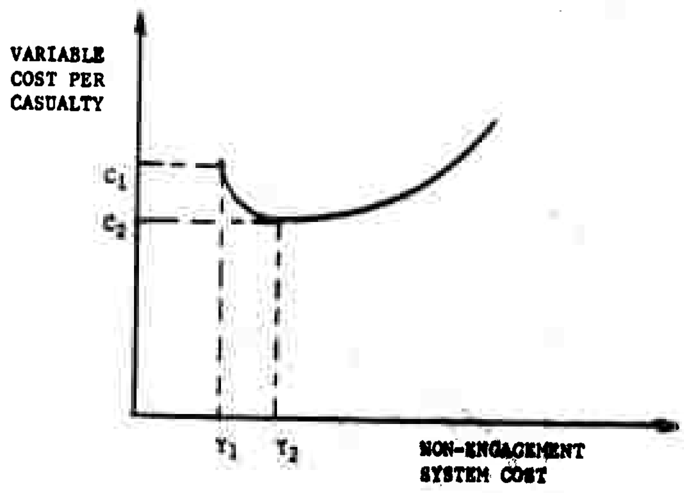


Figure 3.3 VARIABLE COST PER CASUALTY VS NON-ENGAGEMENT SYSTEM COST, CONSTANT CASUALTY LEVEL

Table 3.1

LIST OF SYMBOLS FOR CALCULATING VARIABLE COSTS PER ENGAGEMENT

Symbol	Definition
$\underline{E}_i'$	A vector $(E_1, E_2, \ldots, E_p, E_{p+1}, \ldots, E_{p+w})_i$ of expected attrition of p types of equipment and w types of weapons in scenario i
$\underline{I}$	A replacement cost vector $(I_1, I_2, \ldots, I_{p+1}, \ldots, I_{p+w})$ for the p types of equipment and w types of weapons
$\underline{C}_r'$	A vector of costs per round $(C_{r_1}, \ldots, C_{r_w})$ for w types of weapons
$\underline{R}_i'$	A vector of expected numbers of rounds expended per engagement $(R_1, \ldots, R_w)_i$ for the w types of weapons in scenario i
TVC_i	Total variable cost in scenario i $TVC_i = \underline{R}_i' \, \underline{C}_r + \underline{E}_i' \, \underline{I}$
K_i	Required number of casualties per engagement for scenario i
C_i	Average total variable cost per casualty per engagement in scenario i. $C_i = TVC_i/K_i$
$\underline{C}$	A vector of the variable costs per casualty for the scenarios. $\underline{C} = (C_1, C_2, C_3, C_4)$
$\underline{Y}$	A vector of the non-engagement system costs for the scenarios. $\underline{Y} = (Y_1, Y_2, Y_3, Y_4)$

3.2 THE MEASURE OF EFFECTIVENESS

The criteria for the artillery system, or the measure of effectiveness (MOE), has been briefly mentioned as the problem of simultaneously minimizing the variable cost per casualty per engagement and the non-engagement system cost. As stated, the problem is one of minimizing a two-component vector consisting of variable cost per casualty and non-engagement system cost, and each of these two components is again another vector consisting of four components each. The components of variable cost and non-engagement system cost correspond to the calculations obtained in the four scenarios using the notation as given in Table 3.1. In notation, the criteria is

$$\text{Minimize } (\underline{C}, \underline{Y})$$

where $\underline{C}$ is the vector of variable costs per casualty and $\underline{Y}$ is the vector of non-engagement system cost. More details of vector minimization will be discussed in Chapter V, but for now the details of determining the components of the $\underline{C}$ and $\underline{Y}$ vectors will be examined.

If it happens that the system characteristics are determined and the non-engagement system cost estimated before any prototypes are built, then the continuous function outlined in Figure 3.2 would apply. If several discrete prototypes were currently in being, the criteria might be modified somewhat to

$$\underset{j}{\text{Minimize}} \quad (\underline{C}, \underline{Y})_j \quad , \quad j = 1,2,\ldots,n \quad \text{and } n = 2$$

which indicates that each discrete alternative j will be analyzed and costed for its values of $\underline{C}$ and $\underline{Y}$, j taking on the values one to n and n is greater than or equal to two. The optimum solution will be that alternative which simultaneously has minimum $\underline{C}$ and $\underline{Y}$ vectors over all alternatives. If this unique solution does not exist, i.e., there is at least one other vector which has either $\underline{C}$ or $\underline{Y}$ vector which is less, then trade-offs and secondary criteria must be considered. This will be discussed further in Chapter V.

The Variable Cost per Casualty Vector. Table 3.1 defines some of the values necessary in obtaining the value of the variable costs per casualty for the various scenarios. Basically, the variable costs per casualty are made up of the costs of combat attrition on the system and the cost of the ordnance expended on the enemy targets in the engagement. The vector $\underline{E}_i$ in Table 3.1 has components which are the numbers of each type of equipment, men, and vehicles enumerated one through p, and the numbers of weapons by type one through w which are expected to become casualties due to enemy action or as a result of combat against the enemy in an engagement in scenario i. The vector $\underline{L}$ has as components the replacement costs of each of the components of $\underline{E}_i$, and the inner product of these vectors, $\underline{E}_i' \underline{L}$, gives the attrition costs per engagement for scenario i. One note of caution is that the cost of replacement associated with personnel is only the training and transportation costs involved in replacing personnel casualties and is not a price tag on human life. It may be assumed that all personnel losses will be equal among all alternatives for any given engagement, and the need to consider friendly personnel losses per engagement will be eliminated. If it is deemed that personnel losses must be considered for all alternatives, regardless, then one solution might be to put such a high price on each human life that no one could argue about it and include this cost in the variable cost per engagement. This is usually impractical because of social, religious, and emotional reactions. A more realistic solution might be to change the criteria to include the expected number of friendly personnel casualties,

$$\text{Minimize } (\underline{C}, \underline{Y}, \underline{Q})$$

where the vector $\underline{Q}$ is a vector of expected friendly casualties, one component corresponding to each scenario.

The sources for determining the expected values of the components of $\underline{E}_i$ may be varied. Past combat experience will give some guide as to personnel and vehicle losses that may be expected for a given sized engagement. However, new technology, engineering, tactics and environment effects will influence the vulnerability and the consequent combat attrition of all system components, including personnel. Past experience must be tempered, then, with judgment and a full appreciation of current friendly and enemy capabilities. Possibly a better estimate could be obtained by programming enemy capabilities into standard war-game simulations, and analyzing their results against friendly forces in the computer iterations. [16]

The replacement cost vector $\underline{I}$ and the vector of costs per round $\underline{C}_r$ are simply the costs of replacing the combat attrited or combat expended components of the system. However, $\underline{R}_i$, the vector of expected number of rounds expended per engagement is not so straightforward. Each component of $\underline{R}_i$ is an expected number of rounds calculated according to the formulas given in Appendix I, and the components, when summed, will be the number of rounds required to inflict the desired casualty level K_i in each scenario i.

Using a standard derivation under the assumptions stated in Appendix I [16, 18], the expected number of rounds required to inflict a given level of casualties K_i per engagement is a function of the area of the target (A_t), the mean area of affectiveness (MAE) of each round, and the circular error probability (CEP). These parameters, A_t, MAE, and CEP, and the factors which affect them are given in Table 3.2

Before discussing the perturbations of these parameters by the various scenarios, some discussion of the number of casualties K_i for each scenario i is in order. The number of casualties K_i is strictly deterministic, and the assumption is that any target which is within the specified mean area of effectiveness (MAE) of a particular bursting projectile will be made a casualty by that projectile. As previously mentioned, MAE will vary as a function of target type, position, hardness, etc. In order to simplify the target and round calculations,

Table 3.2

PARAMETERS AFFECTING THE EXPECTED NUMBER

OF ROUNDS REQUIRED TO ACHIEVE CASUALTY LEVEL K_i

Target Area, A_t	Mean Area of Effectiveness, MAE	Circular Error Probability, CEP
Hard	Projectile design	Random system error
Medium Hard	Caliber, weight	Target location error and
Soft	Velocity	Weapon location error
Coverage effects	Angle of fall	Target reporting method, techniques, time lags
	Height of burst	
	Coverage effects	Coverage effects

all targets may be given in terms of their personnel equivalents. For example, an enemy tank with a crew of four would be thought of as a personnel target with an area equal to that of the tank, and the MAE used would be that of the particular round against tanks. This will reduce casualties per engagement K_i to a single value instead of requiring a vector of values listing all the various target types. Since the casualties per engagement K_i is deterministic, and the variable quantity is the number of rounds required to inflict K_i casualties, it might be desirable to add a probability statement which requires that the probability of achieving K_i is greater than some arbitrary value, say 0.9. This probability statement can be transferred to the expected number of rounds per engagement vector, $\underline{R}_i$, by requiring the expected number of rounds per engagement, which is an average value of expectations obtained over some number of computer iterations, to be greater than ninety percent of the individual expectations found on each computer simulation. In notation this may be expressed

$$P(K_i^* = K_i) = P(m \text{ rounds inflict } K_i \text{ or more casualties per engagement}) = 0.9$$

where K_i^* is a random variable and is the actual number of casualties per engagement. The variable m is a computer-derived expected number of rounds required to inflict K_i casualties per engagement.

The variable cost per casualty, from Table 3.1, is seen to be the product of expected attrition times attrition costs plus expected round expenditures times cost of rounds all divided by the number of casualties per engagement K_i. The next question that might be asked is, how is the variable cost per casualty affected by the scenario.

Weapons will have a certain set of conditions under which they will function and perform optimally, and these conditions will be considered prevalent in the non-existent Ideal Scenario. The MAE of each round will realize its physical limits in the ideal scenario, the uncertainty of the locations of the artillery weapon and the target will be minimized and will reduce the CEP to a function of the random error of the weapon system only. The expected number of rounds required to inflict K_i casualties per engagement in the ideal scenario will be optimistic with respect to the other scenarios or what may occur in an actual engagement. Attrition due to combat can be expected to be minimized in the ideal scenario, and a lower bound for variable costs per casualty will be realized with respect to the other scenarios and actual engagements.

In rain forest areas, mapping is usually poor and distinguishing landmarks are usually more obscured by the high tree canopy. [3] As a result, increased uncertainty of the location of the artillery weapon and the enemy target results in greater CEP's. Target area is usually reduced in dense vegetation for command and control purposes, and will result in a smaller probability of hitting the target by a single round, as seen in Appendix I. The observer has a decreased ability to locate and adjust bursting rounds onto the target due to the muffling effect of the tree canopy. Shielding and deflection of the projectiles by the high canopy will tend to reduce the MAE. The total effects of increased CEP, reduced MAE, and reduced A_t will be to increase the expected number of required rounds to achieve K_i.

The effects of high temperatures and humidity associated with the rain forest will tend to increase the numbers of men required to perform a given work load above the number required under ideal temperature and humidity conditions. Preventive maintenance loads may increase due to an environment which is conducive to rust and corrosion. As a result, attrition of weapons and equipment will be expected to increase above that expected in an ideal environment. The total results of increased expected rounds required to inflict K_1 and increased attrition will be an increased expected variable cost per casualty for an engagement in a rain forest over that expected in an ideal scenario.

Desert effects will be a markedly increased attrition of weapons, vehicles, and equipment due to heat, sand, and grit [19], and an increased attrition of personnel under combat conditions due to the effects of heat and low humidity. [3, 12, 26] A desert engagement is characterized by mobility and an increased demand for movement against fleeting targets, resulting in greater-than-ideal scenario wear and tear on vehicles and equipment, contributing further to attrition of equipment. Fleeting targets, effects of heat mirages, dust and sand storms will all reduce the accuracy of locating targets and the effectiveness of adjusting fire onto the targets.

In the mountain scenario the added uncertainty of elevation is added to that of target location and weapon location, resulting in an increased CEP over that obtained if locations and elevations are exactly known. By geometry[1] it is seen that the effective CEP against

[1]It will be more if the projectiles fall at an angle less than 90° onto a reverse slope of 30°. Firing at a fixed point P, half of the rounds would be expected to fall within a horizontal circle of radius r. On a 30° slope, the same cone of fire projects to an ellipse with a minor radius of r and a major radius of r/cos 30°. The new area, instead of being pi times r^2, is now pi times r^2 divided by cos 30° for an increase of 16% over the horizontal CEP.

targets appearing on reverse slope terrain may increase by as much as 16% on a 30° slope due to the slope alone. However, CEP's will be reduced on forward slopes by the same analysis. Uncertain and variable meteorological conditions and the added burden of maintaining observation of reverse slopes by air or other means increases CEP's and attrition costs respectively.

Mountain masses tend to mask or shield the fire of some weapons and will place an increased requirement on high angle fire weapons. High angle fire is characterized by greater CEP's and smaller caliber weapons with smaller MAE's. Mountain masses will also channelize communications and logistics routes increasing the vulnerability to ambushes and enfilade fire and the expected attrition to an engagement. The overall effect will be an expected variable cost per casualty greater than that expected in the ideal scenario.

<u>The Non-Engagement System Cost Vector.</u> Returning now to the basic model presented at the beginning of this section, consider the second component of the measure of effectiveness vector ($\underline{C}$, $\underline{Y}$). The non-engagement system cost component $\underline{Y}$ is itself a vector composed of four components Y_i, which correspond to the non-engagement system life costs in each scenario i. The adjective 'non-engagement' is added to indicate that the system cost considered here does not include the variable costs that arise solely in the combat engagement. Such items as training ammunition and normal stocks of spare parts are included in the non-engagement system cost, but combat attrition and expenditures of ammunition against an enemy are not. For any alternative being considered, its minimum non-engagement system cost will be realized in

the ideal scenario because weather and terrain conditions will be ideal, resupply and movement will be unrestricted, and maintenance and operating conditions will be optimum.

Some of the effects of the rain forest on the non-engagement system cost are those due to heat and humidity. Weapon and equipment life cycles are shortened as a result of mildew, rust, and corrosion resulting in higher total replacement costs over a given period of time. Personnel do not perform as well in excessive heat and humidity, and this requires greater numbers of personnel plus greater numbers of replacements to accomplish the workload.

Due to the high canopy and excessive vegetation, fewer firing positions will be available. Mobility of the basic weapon will be reduced and there will be a requirement for special vehicles as a result of lack of roads and trails and the existence of excessive vegetation [3]. Requirements may be generated for more or perhaps new observation components for detecting enemy targets beneath the canopy. The canopy will inhibit or mask the firing of the weapons on targets at certain ranges and will place an increased operational requirement on the mortars and howitzers. The overall firing rate and firing capability will be impaired as a result. In the event the enemy artillery has well-prepared positions, increased vulnerability to enemy counter battery fires may result.

Low humidity and high temperatures such as are found in the desert scenario reduce the life cycles and the work cycles of equipment and men. Preventive maintenance intervals will be shorter due to sand and dust and chemical breakdown of lubricants due to excessive heat. Greater numbers of personnel will be required to perform the increased maintenance work load and to compensate for the debilitating effects of desert heat. [2, 19, 28] Logistic support requirements will be increased due to maintenance and personnel requirements and due to the nature of desert warfare, i.e., warfare that is characterized by mobility and slashing maneuvers of mobile troops. [3] The total effects of the desert scenario will be to increase the non-engagement system cost over that expected in an ideal scenario.

In the mountain scenario, mountain masses will tend to channelize communications, inhibit mobility and freedom of movement, and place a requirement on the system for a greater number of high angle of fire weapons to meet the firepower requirements. Higher altitudes and low temperatures will tend to reduce the tempo of operations due to human tendency to fatigue more rapidly in these conditions. Above certain altitudes helicopters may become ineffective for tactical and logistical support. These factors combine to result in a reinforced artillery system when compared to that required in the ideal scenario.

To summarize, the non-engagement system cost will increase as humidity and average rainfall decrease to desert conditions from a standard day or ideal conditions. Non-engagement system cost will also increase as humidity and rainfall increase to rain forest conditions from the standard day or ideal conditions. Desert conditions will require increased operations and maintenance costs, increased personnel costs, and increased logistics costs. Rain forests may require more firing units since mobility is hampered, or may require more helicopter units to attain an acceptable capability to displace rapidly. Mountains require a preponderance of high angle of fire weapons, an increased observation system to observe reverse slope terrain, and increased firepower means to overcome the vulnerability imposed by channelized communications. Also, higher altitudes will cause a loss of efficiency of personnel and support helicopters.

3.3 THE CONSTRAINTS

The basic constraints to the solution of the model proposed in this section are given in section 3.1. The first is that the non-engagement system cost be equal or less than the budget. As developed more fully in Chapter IV, all the costs do not normally occur at one single point in time, so that the system costs are incremental over some period of time. These periodical costs should be equal to or less than the planned budget before their associated alternative is even considered as a possible solution. The second constraint requires that the casualties inflicted per engagement is greater than or equal to the number specified. If the alternative system cannot inflict the degree of destruction required, there is no need in examining that particular alternative. The third constraint was that the number of targets per engagement must be specified, although this may be thought of more as an assumption than as a constraint since it does define the engagement.

Four other constraints are implicit in those stated in section 3.1 and should be mentioned. The first implied constraint concerns the maximum range of the system. The minimum acceptable maximum range must be stated to provide for the counter battery task in each scenario. The second implied constraint is that of continuous coverage, i.e., the proposed alternative mix of mortars, howitzers, and guns must provide artillery coverage from the forward edge of the battle area (FEBA) continuously to the minimum acceptable maximum range stated above.

If holes exist in the artillery coverage, the enemy need only slip his own artillery into such a 'hole' and decimate friendly artillery at will. The two remaining constraints which will be discussed a little more at length are the implied mobility constraints and the implied technological constraints.

A weapon which could devastate any known target with one single shot out to a range of ten miles at a cost of only five dollars per round would have limited use, in most instances, if it could not be transported on a ship, lifted by an aircraft, or pulled by a truck. If this mythical weapon could be instantaneously manufactured at any chosen spot, all the transportation restrictions might be circumvented. However, in the usual instance, mobility, the characteristic of displacing from one position to another to engage in combat, adds to the effectiveness of the system. A weapon or vehicle that is described as being highly mobile is usually capable of moving across various types of soils inclined at various slopes at speeds described as fast or good. How mobile is 'highly mobile' and how fast is 'good'?

One method of quantifying the mobility characteristics of a system is to define the constraint vector $\underline{T}$ which is a vector of the minimum times in each of the scenarios for any battery of a system to displace a given specified distance in each scenario and to commence firing on the new target from the new firing position. The standard distance in each scenario might be some fraction of the maximum range of the weapon mix, and would contain typical terrain, vegetation, and obstacles representative of the scenario. Each component T_i of the vector $\underline{T}$ would correspond to a scenario i, and would be measured from the time the first artillery tube of the particular battery ceases firing and begins the displacement until the time the last weapon of the battery which is displacing begins firing on the new target from the new position. This vector of displacement times $\underline{T}$ would be required to be less than some maximum allowable times,

$$\underline{T} \leq \underline{T}_{maximum}$$

where $\underline{T}_{max}$ is arbitrarily assigned or may be a vector of the average times of the current operational system in displacing over the prescribed distances and obstacles in each scenario.

The times to displace will be some function of the weapon weight, the scenario, and the technology of the mobility mode selected, i.e., whether the weapon is towed, self-propelled (SP), an amphibian, or helicopter transported. The determination of the optimum mode or mix of modes for artillery mobility is a topic for another research paper.

Technological constraints exist which relate weapon system characteristics to the measure of effectiveness (MOE) of the alternative. Stating that relationship may be something of a problem, but there is a recognized limit to the current state-of-the-art. Current technology can only do so much, projectiles can be made to have only some maximum MAE and inflict only so many casualties in a given area, helicopters can fly only so fast in displacing artillery units, etc. The components of the variable cost per casualty vector $\underline{C}$ are functions of attrition, replacement costs, expected expenditures, and costs per round of ammunition, or

$$C = F_1(\text{attrition, replacement cost, number of rounds fired, cost per round of ammunition, caliber of round})$$

and each of the components are functions of other variables. Attrition will be a function of temperature, humidity, terrain slope, number of moving parts in the piece of equipment, number of enemy targets opposing, number of rounds fired, and others. Equipment replacement costs and ammunition costs will be functions of equipment or weapon weight and size, calibre, number of moving parts, maximum range of the weapon or round, etc. The number of rounds fired to defeat the target will be a function of MAE and CEP which in turn are functions of the weight of the round, muzzle velocity, rate of fire, range to target, canopy height, caliber, angle of fall, height of burst, location error, and others as indicated in Table 3.2. Standard regression programs exist at most computer facilities, and these programs will use past data of weapon types to compute coefficients of the parameters to define an approximate function F_1 for predicting C. However, the value of F_1 for predicting C when the new alternative characteristic parameters are outside the ranges of values of the past data requires judgment. If all the past calibers have been in the range from 81mm to 175mm, F_1 might not be so useful for extrapolation in estimating C for a 250mm weapon.

If continuous second partial derivatives of F_1 could be assumed or determined, perhaps a better use of F_1 would be to determine the minimum C by the classical method of setting the first partial derivatives with respect to the parameters equal to zero and solving the resulting set of simultaneous equations.

In like manner, the non-engagement system cost Y is some function of the number of targets per engagement, the temperature and humidity, slope of terrain, caliber of weapon, and the mobility mode cost, among others. By regression analysis, some function F_2 could be determined which should have a shape similar to Figure 1.5. The minimum Y will now depend on the desired casualty level, the required mobility mode which meets time constraints, environment parameters, and others, and will be determined from the graph by picking off a Y for a given casualty level K_1. The same restrictions pertaining to the use of F_1 apply to the use of F_2.

IV THE COST MODEL

4.1 DISCUSSION

Costing is the other side of the weapons-system-evaluation coin, effectiveness being discussed previously. A myriad of references present the rationale, logic or reasoning behind costing and the various techniques employed in costing a system. [1,2,4,6,27] Two approaches may be taken depending on whether the alternative being evaluated is a prototype weapon which has been independently developed or whether the alternative is a new weapon to be designed and developed. Historically, artillery weapons have usually been the result of the former process. However, for costly alternative systems of the future some derivation of cost estimating relationships (CER's) may be necessary, since prototype production may be too costly.

Most authorities divide the weapon system cost analysis problem into three parts: research and development, initial investment, and annual operations and maintenance costs. The cost elements might look like Table 4.1, where a cost element is a source or unit of the system or system support which requires dollars for purchase or operation.

Some typical problems in evaluating cost elements should be mentioned. Determining system requirements from testing of the complete system, item I.c in Table 4.1, is often done by deriving expected values from war game simulations, especially for ammunition requirements. Weapon and shell characteristics are programmed into the computer, an array of targets is advanced against the gun positions, and the computer calculates how many rounds were fired to achieve a certain level of casualties. Since it is impossible to place an entire system in the

Table 4.1 TYPICAL CLASSIFICATION OF WEAPON SYSTEM COST ELEMENTS

I. Research and Development

a. Preliminary research and design studies

b. Design and development of subsystems

c. Test of the complete system

II. Initial Investment

a. Prime mission equipment

b. Support equipment

c. Initial spares, spare parts and stocks, ammunition

d. Initial training

e. Initial travel, transportation and miscellaneous

f. Military installations

III. Annual Operations

a. Pay and allowances

b. Equipment and installations replacements

c. Equipment and installations maintenance

d. Replacement training

e. Consumables, POL, training ammunition

f. Recurring travel, transportation, miscellaneous field and employ it against an actual enemy to test it, computer simulations are probably the most feasible and least costly method of testing a system. It is well to keep in mind a few limitations of the computer analysis, however.

The first limitation concerns the expected number of rounds required to inflict the given casualty level K_i. If M is the number of rounds required to inflict the casualties, M has some mean m and some variance σ^2. One value of M is observed on each computer run, and the total sample of M's over some number of computer iterations is used to estimate m. However, it is just as important to know something of the range of values M takes on and how often M falls within that range. The variance σ^2 gives some idea of that range of values, and was used by Chebyshev to show that the probability that M will exceed its mean m by more than some multiple of the standard deviation σ is less than the inverse square of the multiplier of σ. For example,

$$P(|M - m| > h\sigma) \leq 1/h^2 ,$$

or the probability that the required number of rounds to neutralize a target exceeds the mean value m by more than h standard deviations is equal or less than $1/h^2$. If h is two and the standard deviation is 9, then the probability that the number of rounds required to neutralize a target varies from the mean by more than 18 is equal or less than $1/h^2$ or one-fourth.

The second limitation concerns simulation programming. It is difficult to simulate topography, target detection and location problems such as poor visibility and jungle canopy, and maneuvering forces. All weapon types are assumed to perform equally well for the given computer simulation, when such is not the case. Most scenarios for computer simulations are specific locales, geographical locations, and consider little more than significant barriers to movement and major topological features.

Another difficult problem that may arise in determining total system cost is the problem of joint costing. If a costing unit such as a helicopter squadron is common to two or more other systems such as artillery and infantry, it may be a difficult chore deciding just what fraction of the helicopter effort and resultant helicopter squadron cost should be attributed to the artillery. The usual rule is to determine, as nearly as possible, the usuage by the various systems of the common unit, and assign the cost of the common unit accordingly. If the helicopter squadron mentioned above is based aboard an LPH, the problem is extended once more: what portion of the total LPH cost goes to support the helicopter squadron which is supporting the artillery?

Some costs should not be considered in comparing alternatives. If certain facilities are already available, or a required subsystem is common to all proposed alternatives, then these need not be considered in the cost-effectiveness analysis. The first case is an example of 'sunk costs', money which has been irretrievably spent on a subsystem or a support element, but the subsystem or element still has some value remaining. If somehow the old facility could be used for some other purpose besides supporting artillery, then the value to the other purpose besides artillery would have to be considered as an opportunity cost and would be included in the artillery system cost. The RDT&E costs and the initial investment costs of the current system are examples of sunk costs and will be omitted when comparing new alternatives to the current system. Only attrition and annual operation and maintenance costs need be considered when comparing the present system against some alternative. In the second instance above, that of a required subsystem being common to all proposed alternatives, only the planning budget constraint must be met, i.e., the cost of the common subsystem + the cost of the proposed alternative must be equal to or less than the planned budget. Consideration of the costs of each alternative need not include the cost of the common subsystem.

4.2 THE PROTOTYPE MODEL

Before evaluating a newly proposed artillery system against the current system, it is necessary to have a standardized costing procedure. If there is any bias in a costing technique, it is hoped all alternatives will become equally biased by using the same procedure for all, and that the ordering of the alternatives will remain the same. The cost matrix in Figure 4.1 outlines a costing procedure for the current system by omitting the XX items. The system costing will break down into five broad categories of costing elements: the basic artillery unit, usually a battery; the targeting and fire control subsystem; facilities; surface ship-to-shore transfer craft; and vertical assault/support squadrons. For each costing element the following items must be taken into account: RDT&E, investment costs, maintenance and attrition, personnel of the unit, support personnel who are attached to the unit or support the unit from some rear echelon, POL and other consumables, and shipping requirements.

<u>Current System</u>. For the current system all RDT&E and investment costs are sunk costs and need not be considered. Personnel, maintenance and attrition, and POL and other consumables costs are historically

TYPE COST UNIT	ANNUAL COST						
	RDT&E	INV	MAINT & PARTS	PERS	SPT PERS	POL	SHIPPING
Battery							
Artillery Piece	XX	XX	X	X	X	-	LST
Prime Movers	XX	XX	X	X	X	X	LST
Support Vehicles	XX	XX	X	X	X	X	
Ammo	XX	XX	-	-	X	-	
Target Detection	XX	XX	X	X	X	-	
FDC	XX	XX	X	X	X	-	
Shore Facilities	XX	XX	X	X	X	-	-
Surface Ship-Shore							
Transfer Veh	XX	XX	X	X	X	X	LPD
Assault Amph	XX	XX	X	X	X	X	LPD
Vertical Assault							
Helicopters	XX	XX	X	X	X	X	LPH
SPT Equip	XX	XX	X	X	X	X	LPH
Facilities	XX	XX	X	X	X	-	-

Figure 4.1 COST MATRIX FOR AN ALTERNATIVE SYSTEM

documented and are readily available. As previously noted, major problems may present themselves in apportioning the proper fraction of costs of shipping, support equipment and personnel, facilities, and surface/vertical assault/support to the artillery battery. If any of these are common to all alternatives, they may be omitted from the costing effort.

Using vector and matrix notation, it is pc ible to set up the problem of determining total battery costs, $B_{i\ total}$, for computer computations. Let the numbers from Figure 4.1 be compiled into the battery cost matrix A_i where the subscript i refers to battery type for n types of batteries. Define a vector $\underline{B}_i$ which will be a vector of coefficients or multipliers corresponding to the costing units listed in the left column of Figure 4.1 for a total of twelve components in the vector. Then define $\underline{B}_i$* as a vector of costs, each cost component of the vector corresponding to a column of the Figure 4.1, excluding the first or left hand column. In notation,

$$\underline{B}_i^{*\,\prime} = \underline{B}_i{}' A_i$$

and from this equation,

$$B_{i\ total} = \underline{1}' \underline{B}_i^*$$

where $\underline{1}$ is the sum vector. If there is a discount rate r being applied, then

$$B_{i\ total} = \underline{D}' \underline{B}_i^*$$

where $\underline{D}'$ is a vector of discount factors and B_i is now the present value of the discounted battery costs.

For a simplified example consider the following hypothetical Type 1 gun battery.

$$A_1 = \text{the cost matrix similar to Figure 4.1}$$

$$= \begin{pmatrix} 0 & 0 & 100 & \cdots\cdots\cdots\cdots\cdots & 0 & 100{,}000 \\ \cdot & \cdot & 150 & \cdots\cdots\cdots\cdots\cdots & 25 & \cdot \\ \cdot & \cdot & \cdot & \cdot \quad \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \quad \cdot & \cdot & 50{,}000 \\ 0 & 0 & 375 & \cdots \quad \cdot \quad \cdot & \cdot & 0 \end{pmatrix}$$

Each column of A_1 corresponds to one of the columns of Figure 4.1. Each element of each column represents an average marginal cost per unit of the cost units in the left hand column. In this hypothetical example, the RDT&E and investment costs are sunk and the elements of A_1 corresponding to these are all zeroes. The annual cost of maintenance and parts per artillery piace is 100, cost of shipping per artillery piece is 100,000, etc. $\underline{B}_1'$ is the vector of coefficients of the number of units to be costed, and in this hypothetical example is (6, 6, 10, 200, 0.1, 0.3,........) where the fractions represent that portion of the support subsystem utilized by battery type B_1. In this instance 0.1 of the target detection subsystem effort is utilized by battery type 1. The vector of costs attributable to RDT&E, Investment, Maintenance and Parts, etc., is

$$\underline{B}_1^* = \underline{B}_1' A_1$$

and the total cost of battery type 1 is

$$B_1 \text{ total} = \underline{1}' \underline{B}_1^* \text{ if the discount rate is } 0\ \% \text{ and}$$

$$= \underline{D}' \underline{B}_1^* \text{ where } \underline{D}' \text{ is a vector of discount factors if } r \text{ is the discount rate.}$$

If there are n types of batteries and m_i of each battery type, then the total lifetime operating cost for the artillery system being considered is

$$Y = \sum_{i=1}^{n} m_i \, B_{i \text{ total}}$$

The time phasing of costs and the discounting procedures which may be employed are discussed in section 4.5.

The rigorous and arduous task of determining matrices A_i for all types of artillery batteries may seem overly burdensome at first. However, the task is required in order to accurately determine total lifetime operating systems cost, time phasing of costs, cost of adding one additional battery of type i, and for developing reliable Cost Estimating Relationships (CER's) for proposed future alternatives. The CER's will be predictors which will hopefully accurately relate such items as maintenance and operating costs and attrition costs in a particular scenario to the investment costs and the characteristics of the alternative. Another useful CER will be one relating the weight and volume of an alternative to its shipping or helilift costs.

Other results of the rigorous development of the cost matrices will be a determination of those cost items which are relatively insensitive as to battery type and those items which may be common within or between battery types. For example, the costs of the targeting and fire control subsystem are probably relatively constant from battery type to type. Within all batteries of a particular type, it would not be unreasonable to expect all personnel requirements to be the same, perhaps the numbers of required support personnel as well. Analyzing the output of the costing matrices of two or more alternatives will be discussed in Chapter V.

The Prototype Alternative. The basic cost matrix in Figure 4.1 applies with the columns for RDT&E and Investment included where applicable. Again, RDT&E and investment costs of components of the current system are sunk costs and are omitted from the costing of any alternative which incorporates those components. The same computer programs used to evaluate the current system will be used for the alternative. The CER's developed from data on current systems will be used to estimate such items as proposed alternative operations and maintenance costs, personnel costs, etc., provided the characteristics of the proposed alternative are comparable to those of the system on which the CER's were based. The validity of the CER's cannot be assumed for all possible alternatives.

The costs for RDT&E in developing the prototype are historical and will prove useful in predicting initial investment costs for the alternative, i.e.,

initial investment cost = f (RDT&E, weapon characteristics)

where the RDT&E costs may reflect the degree of technological sophistication of the alternative. If the RDT&E costs are considered sunk costs for the company developing the prototype, they will be recovered by an increased investment cost. If RDT&E is on-going, the costs will be time phased over some expected period of development and will be discounted at an accepted discount rate.

Initial procurements will likely be time phased rather than a lump sum purchase, if for no other reason than that the manufacturing rate has some limit. The training of personnel to operate the new equipment will be phased over some time, as well, and it would be uneconomical to have large inventories of the new weapons on hand for any great length of time prior to the completion of training of the personnel to operate them.

4.3 NEW DESIGN COST MODEL

The new design will be limited by technology and the state-of-the-art of artillery systems. Relating these designed weapon characteristics will be the job of CER functions such as those discussed in section 3.3. For example, the variable cost per casualty, C, and the non-engagement system cost, Y, can be estimated from their parameters:

$C = F_1$ (weight of the weapon, weight of the projectile, length of the tube, muzzle velocity, rate of fire, range to the target, number of enemy targets, number of moving parts per weapon, temperature, humidity, height of burst, angle of fall, etc.)

$Y = F_2$ (number of targets, mobility mode cost, caliber of weapon, projectile weight, temperature and humidity, etc.)

After the characteristics have been selected, the CER's will be used to estimate all the items of the cost matrix in Figure 4.1 that apply to the proposed alternative. Estimates must also be made of the time phasing of RDT&E and production schedules for the initial investment so that appropriate discount factors may be applied to the cost items.

Past history has shown the feasibility of the prototype method of developing a proposed alternative, although to determine if it is the optimum method would require further research. It is likely that pure cost estimating will be less costly than the prototype approach for weapons requiring large outlays for RDT&E and initial investment or for testing and evaluation. Just how large is 'large' would be one result of the proposed paper.

4.4 MARGINAL COSTS

The requirement exists for knowing the marginal cost with respect to the current base system of one more battery of each particular type. When considering proposed alternatives, increasing the present system by 1,2,.... batteries should be one of the proposals evaluated. The average marginal cost will vary with the number of additional batteries proposed, but should be considered in the light of potential future growth tendencies of force units requiring artillery support. Also, the average marginal costs of additional batteries will reflect the costs that might be incurred in the event that a conflict results in ballooning of forces. Two cases will be discussed, when excess capacity exists capable of manning and supporting an additional battery, and when only partial or no excess capacity exists.

If excess personnel, facilities, and other support are available to handle the additional increment of artillery being considered, then only the initial investment costs of the weapons and attendant special support equipment plus the operating and maintenance costs need be considered in the marginal cost of the battery. However, the excess capacity implies inefficient use of some of the affected resources, and that the actual operating and maintenance costs of the additional battery will be less than the average of the other batteries of the same type. In fact, in this instance the additional operating and maintenance costs will consist only of the attrition costs and the consumables costs. Historically, this case seldom if ever exists. Manpower is always a problem, and excess facilities occur only during the logical planning for future expansion, and are not really 'excess' at all.

Partial or no excess capacity is the more usual case when considering the marginal costs of one more battery. The same base is usually capable of handling one more unit at the expense of a few more buildings and a few additional support personnel. The costs of the new buildings and the few extra support personnel would be directly attributable to the added artillery battalion, but the cost of the land on which the buildings were erected would not as long as they were erected on the base property. If two, three or more additional batteries were to be considered as an alternative, then their average marginal costs might well involve the full cost matrix of Figure 4.1 less the RDT&E costs.

4.5 TIME PHASING OF COSTS, COSTING SCHEMES AND DISCOUNTING

A typical system that is built and implemented from scratch might have an expenditure sequence that looks like Figure 4.2. For systems as stable and long-lived as artillery, as contrasted with short-lived computer systems for example, the careful phasing and programming of the future costs are necessary to determine the true alternative costs when any discount rate ~~greater than 0 % is considered.~~ [2] Just what that discount rate r should be is the subject of considerable debate and is another research topic. [25]

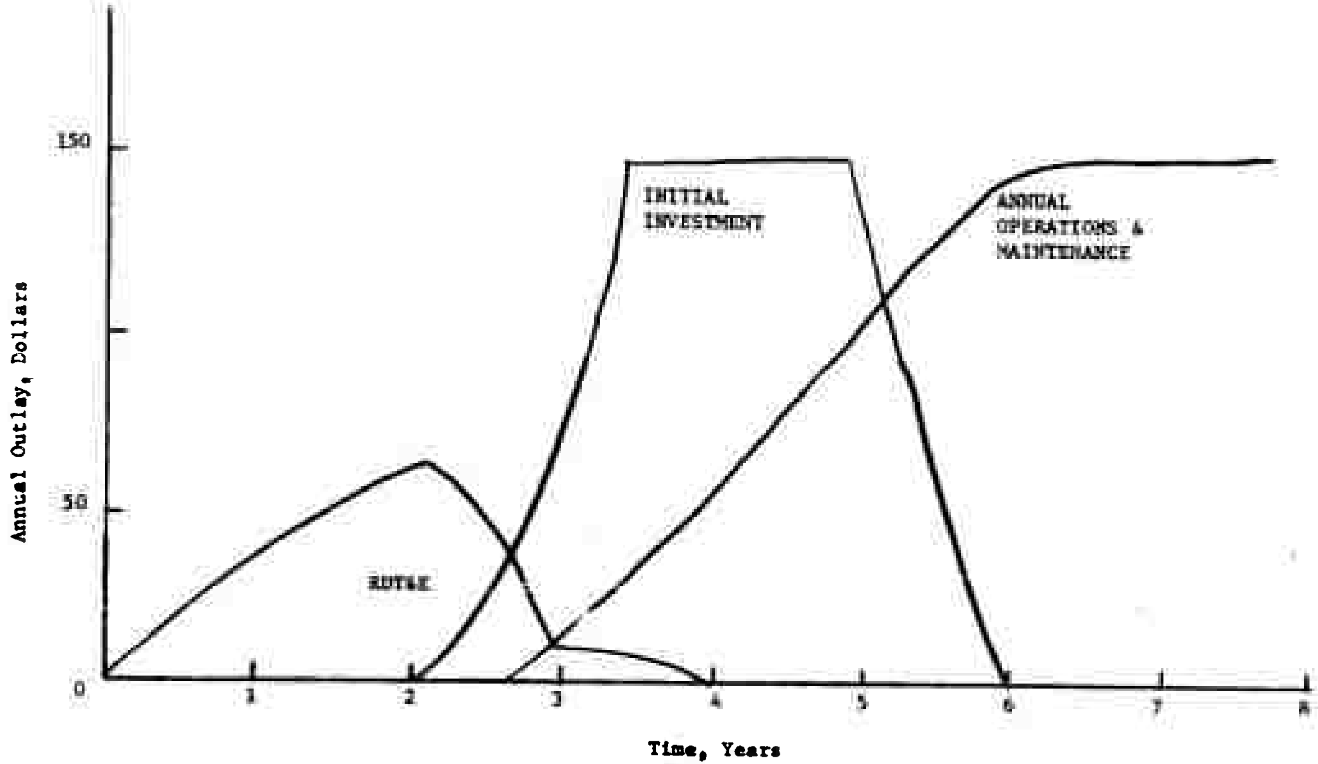


Figure 4.2 HYPOTHETICAL EXPENDITURE PATTERN

Five-Year System Cost. The main advantage of the simplicity of this method is over-shadowed by the dangers of omitting seemingly minor costs such as build-up costs, and the omission of time value and unequal lifetime considerations. [2] RDT&E costs are added to initial investment costs and the estimated costs of operations for five years. It is usually assumed that operating costs do not vary over the five years. The hope is that the relative costs of the alternatives are not unduly influenced by the choice of the five year base and the lack of careful time phasing of costs. This method assumes no time value of money.

Present Cost. Using the present cost scheme, cost streams are discounted to their equivalent present values, and the time horizon is chosen as the least common multiple of the estimated life times of the alternatives. As mentioned previously, the concepts of discounting and the selection of a proper discount rate are discussed in many sources. [2, 25, 27] A primary requirement for the use of the present cost technique is the careful preparation or estimation of the yearly incidence of the costs related to the alternative. Several discount rates may be stated and their results compared.

Annual Cost. Costing by this technique is similar to the present cost method discussed above, except that total system costs are transformed to an equivalent uniform annual amount by dividing the total cost by the number of operating years. Least common multiple lifetimes are used, and if the discount rate is taken to be zero percent for a system whose life is five years, annual cost would be very similar to the five year cost simply divided by five.

The following hypothetical example compares alternative cost streams for two fictional alternative defense systems, and is taken from Appendix B of [2]. Buildup costs are omitted for simplicity of presentation, and would normally be shown in the present cost and annual cost techniques. Alternative A is represented by a cost pattern requiring an initial investment now of $1000 and recurring annual costs of $100. The lifetime of A is ten years. Alternative B is an existing system whose annual operating costs are expected to increase by a uniform amount to extend its operational life. In this comparison, alternative B is favored by all techniques except for present cost estimated at five percent over twenty years and annual cost at five percent for twenty years.

Alternative	A		B	
Non-Recurring (N)/Recurring (R)	N	R	N	R
End-of Year				
0	1000		0	
1		100		120
2		100		140
3		100		160
4		100		180
.	(Etc thru' year 10)			(Increasing
.				by $20 per
.				year)
Estimated Operational Life, years	10		Indefinite	
Total System Cost, Dollars				
1. Five Year System Cost	1500		800	
2. Present Cost 5%, 10 years	1772		1560	
5%, 20 years	2861		3646	
10%, 10 years	1614		1196	
10%, 20 years	2236		2130	
3. Annual Cost 5%, 10 years	230		202	
5%, 20 years	230		278	
10%, 10 years	263		195	
10%, 20 years	263		250	

Figure 4.3 ALTERNATIVE COST STREAMS SUMMARIZED

V COST-EFFECTIVENESS AND DECISION CRITERIA

5.1 DISCUSSION

In the problem as developed by this paper, effectiveness is held constant for all competing alternatives and the costs vary according to designs and weapon characteristics. An engagement has been defined by numbers and types of targets and the level of casualties has been fixed per engagement. Through computer simulations or through straight calculations of projectile effects, CEP effects and scenario effects, expected numbers of rounds per engagement plus attrition costs will transform into expected cost per casualty per engagement. The next question is: How does one take the estimated non-engagement system cost and the expected cost per casualty values for each system alternative and make a selection of a system to be used?

5.2 THE CRITERIA

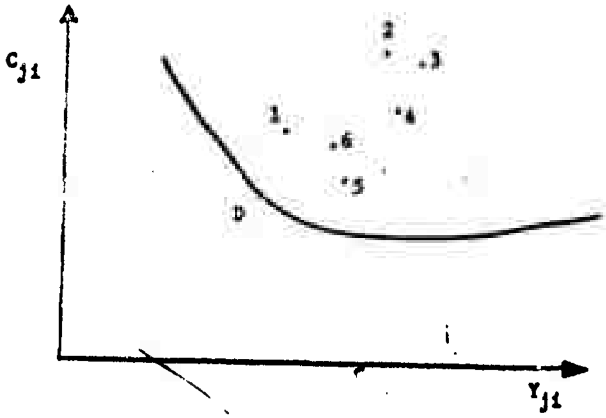
From the chapter on effectiveness, consider a plot of the coordinates of the objective function: Minimize $(\underline{C}, \underline{Y})_j$ over the alternatives j $j = 1,2,\ldots,n$. Such a plot of 7 alternatives might resemble Figure 5.1. One plot will be prepared for each scenario ($i = 1,2,3,4$) for a total of four plots. The Y axis corresponds to the non-engagement system cost, and the C axis represents the variable cost/casualty/engagement in scenario i. The efficiency frontier curve, C_i, is as defined in Chapter I.

Simply stated, the decision rule inferred by the criteria above is: Select that alternative j^* which is feasible and which dominates all other alternatives j. In this particular scenario system D clearly dominates all other systems. Dominance is defined here in the standard manner:

$$\text{if} \qquad Y_{Di} < Y_{ji} \quad \text{where } j^* = D \text{ and for all } j \neq D$$

$$\text{and if} \qquad C_{Di} < C_{ji}$$

then system $j^* = D$ dominates all other systems $j \neq D$ in scenario i. Further, if system $j^* = D$ dominates all systems $j \neq D$ over all scenarios $i = 1,2,3,4$ then system D is absolutely dominant over the alternatives considered.



COST/CASUALTY vs NON-ENGAGEMENT SYSTEM COST, SCENARIO i

Figure 5.1

Now consider the case where D has not been determined for one reason or another. For alternatives 1, 5 and 6 the following conditions hold:

$$Y_{1i}, Y_{5i}, Y_{6i} < Y_{2i}, Y_{3i}, Y_{4i} \quad \text{and}$$

$$C_{1i}, C_{5i}, C_{6i} < C_{2i}, C_{3i}, C_{4i}$$

so that alternatives 1, 5, and 6 dominate alternatives 2, 3, and 4 in scenario i. However, the relations between alternatives 1, 5, and 6 are as follows:

$$Y_{1i} < Y_{6i} < Y_{51} \quad \text{and}$$

$$C_{1i} > C_{6i} > C_{5i}$$

and there is no dominance between these alternatives. If conditions were such that a new alternative, (15), could be generated by taking a linear combination of alternatives 1 and 5, i.e., a new mix could be generated consisting of

$$a(\text{Alternative } 1) + (1-a)(\text{Alternative } 5) \quad \text{where } 0 < a < 1$$

then alternative 6 would be dominated by (15) since

$$a\, Y_{1i} + (1 - a)\, Y_{5i} < Y_{6i} \quad \text{and}$$

$$a\, C_{1i} + (1 - a)\, C_{5i} < C_{6i} \quad \text{or}$$

$$Y_{(15)i} < Y_{6i} \quad \text{and}$$

$$C_{(15)i} < C_{6i} \quad .$$

If this new linear combination of alternatives 1 and 5 dominated alternative 6 for all scenarios i, then alternative (15) would be absolutely donimant and would be selected as the optimum alternative.

Consider the case where linear combinations are infeasible due to large research and development outlays or other costing considerations which must be made for each alternative and which would result in some $Y_{(15)i} > Y_{6i}$ for any one or all i. Re-plot Figure 5.1 for all scenarios and determine the set of alternatives for each scenario which dominate all other alternatives in that scenario, but which do not dominate one another, similar to alternatives 1, 5, and 6 in the above plot.

Suppose the results were the following:

Scenario	Dominating Alternatives
1	1, 5, and 6
2	1 and 5
3	5 and 6
4	6

Their plots might resemble the following Figure 5.2.

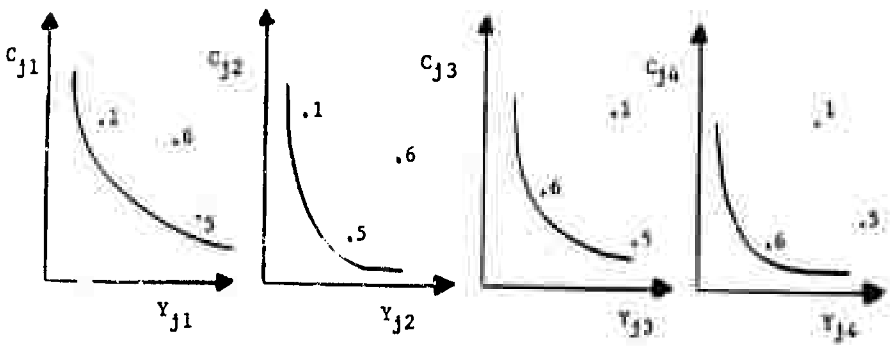


Figure 5.2 PLOT OF THREE DOMINATING ALTERNATIVES

From the Office of the Secretary of Defense or other sources the likelihood of conflict in the various areas of the world would be obtained if possible so that a probability distribution for conflict in scenario i may be derived. Then

p_i = probability of conflict in scenario i

$\sum_{i=1}^{4} p_i = 1$, and define

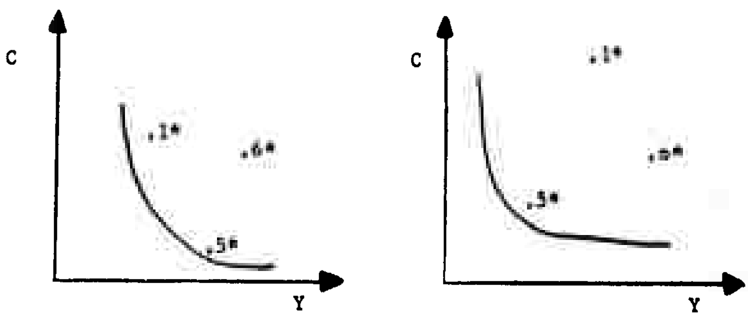
$\underline{P}' = (p_1, p_2, p_3, p_4)$ and

$\underline{V}_j = \underline{P}' \, (\underline{C}, \underline{Y})_j$ where $(\underline{C}, \underline{Y})_j$ is a four by two matrix consisting of the two column vectors $\underline{C}$ and $\underline{Y}$ corresponding to alternative j

$\underline{V}_j$ = the weighted average cost/casualty/engagement and the weighted average non-engagement system cost for alternative j, in this instance $j = 1, 5,$ and 6

$= (C^*, Y^*)_j$

Plot these values of $(C^*, Y^*)_j$ and the results may look like the following Figure 5.3.



CASE A CASE B

Figure 5.3 ALTERNATIVES IN WEIGHTED SCENARIOS

If case B occurs, then the scenario-weighted values of alternative 5 will cause that system to dominate 1 and 6. However, if Case A occurs, resort may be made to other decision considerations such as the effectiveness criteria for mobility. The Defense Department estimate of the expected numbers of engagements per year may be combined with the cost per casualty per engagement criteria as another basis for alternative selection.

5.3 SECONDARY DECISION CRITERIA

Expected Number of Engagements per Year. In the event that no alternative is dominant as defined in section 5.2, the expected numbers of engagements per year may be utilized to select an optimum alternative. From section 5.2, p_i is the probability of conflict in scenario i, given that an engagement or conflict occurs. If it is indicated that E is the expected total number of engagements per year, and that this expectation should hold for the next k years, k = 1,2,...., then

$E_i = p_i E$ = expected number of engagements per year in scenario i

$E_i\ C_{ji}\ K_i$ = expected total variable cost per year in scenario i for alternative j, in this example j = 1 and 5

$\sum_{i=1}^{4} K_i\ C_{ji}\ E_i$ = total variable cost per year for alternative j = 1 and 5

$= TVC_j$

Depending on how far into the future the current expectation E may be projected, k = 1,2,......., and let

$TVC_j^{\ k} = k\ TVC_j$ and define

$Y_j^{\ k} = Y^*_j + TVC_j^{\ k}$ = weighted total expected system cost for k years as differentiated from the non-engagement system cost Y

If it happens that for some j = j* that

$Y_{j*}^{k} < Y_j^{\ k}$ for all $j \neq j^*$ and all k

then system j* is optimum by this method.

Mobility. In the event that all Y_j^k are reasonably close in value, mobility may be used as the discriminating factor in selecting the optimal system j*. Since the alternatives being considered are feasible, they have met the mobility constraints given in the effectiveness chapter. Now consider the following:

$t_j = \underline{P}' \underline{T}_j$ = weighted average mobility time, where P' is as defined in section 5.2 and $\underline{T}_j$ is as defined in Chapter III

The decision criteria becomes: select system j* such that

$t_{j^*} < t_j$ for all $j \neq j^*$, j = 1 and 5 in this example.

VI SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The artillery system is built around a mix of varying types and calibers of artillery weapon batteries. The mix is chosen so that adequate and continuous firepower can be brought to bear on all targets occurring within and from the FEBA forward to some specified minimum-acceptable maximum range. Supporting the artillery batteries, and logically included in the artillery system for costing, are such items as shipping, support equipment and vehicles, and support personnel. For example, ship-to-shore transfer vehicles and helicopter units make up some portion of the artillery system. However, only that portion of the support effort spent on artillery is attributable for costing purposes, and is part of the joint cost problem associated with most systems.

A method for evaluating and comparing alternatives is

MINIMIZE: System Cost

Subject to: Constant effectiveness = fixed number of casualties per engagement

Technological constraints

Budget constraints

where the cost of the alternative is here defined as a vector of two components $\underline{C}$ and $\underline{Y}$ which represent the variable cost per engagement and the non-engagement system cost, ($\underline{C}$, $\underline{Y}$). Effectiveness constraints are defined as the firepower required to achieve the specified number of casualties in each scenario. Achieving the required number of casualties in a scenario results in combat attrition on the system and a number of expected expended rounds from which a variable cost per engagement is derived.

The decision criteria are based on a study of the plot of variable cost per engagement versus the non-engagement system cost for each scenario. Specifically, the decision criteria is:

-- Select that alternative j* such that $(\underline{C}, \underline{Y})_{j*} < (\underline{C}, \underline{Y})_j$ for all $j \neq j*$, that is, select j* such that its cost vector absolutely dominates the cost vector of all feasible alternatives.

-- If no one alternative dominates, then implement secondary decision criteria based on

- probabilities of conflict in each scenario
- probabilities of numbers of engagements per year
- evaluation of mobility vectors

6.2 CONCLUSIONS

The evolving complex artillery system of the future requires a complete cost/effectiveness model for evaluating the entire artillery system under the operating environmental conditions it will likely operate in. The method of minimizing expected variable cost per casualty and non-engagement system cost, while meeting minimum mobility and casualty criteria and staying within budget limits, will select an optimum alternative artillery system. Defining the scenarios in terms of average rainfall, temperature, and terrain slope provides standard environments for comparing alternatives.

Determining detailed costing matrices for the current artillery batteries and support agencies is necessary for several reasons. The matrices will reveal items common to all artillery systems and which are not required for comparing alternative costs. Costing matrices will be useful in developing marginal costs for additional artillery units of the present types. Finally, the matrices will have utility in preparing accurate, reliable cost estimating relationships between research and development costs, investment costs, and weapon characteristics. These relationships will be necessary for developing future alternative systems.

Should no alternative prove absolutely dominant in variable cost per casualty and non-engagement system cost, the secondary decision criteria presented which are based on mobility and/or future expected numbers of engagements will select an optimum system.

VII AREAS OF CONSIDERATION FOR FURTHER RESEARCH

In the process of developing this paper, several subjects have presented themselves for further consideration, the first being the interaction of the artillery system with the naval gunfire support system and the close air support system. What should the future artillery system look like in light of tactical air which includes armed helicopters and the new OV-10, intermediate domain weapons such as the proposed LFSW/LANCE weapons, LAW and MAW? Included should be a sensitivity analysis on the total weighted variable cost and average mobility times T by varying the numbers of engagements per year and varying the probabilities of the scenarios.

Detailed costing matrices and the CER's discussed in Chapter IV require development in conjunction with the evaluation of current experimental artillery prototypes. A cost-effectiveness study of prototypes versus estimated characteristics and costs should be developed. Does it always pay to build a prototype model?

Finally, the effects of the fire control system to include the detection, location, and identification of targets should be studied in relation to the artillery system. How accurate is target detection and location? How much does target location error vary and how does it vary as a function of range from the observer and range from the gun position? How does it vary from scenario to scenario? To what range are targets profitably detected, i.e.; at what range does the artillery system become saturated with targets? What effects do the built-in time delays of the fire control system have on the expected number or rounds required to inflict the required numbers of casualties per engagement?

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APPENDIX I

EXPECTED ROUND REQUIREMENTS

This formulation is a standard derivation and is taken from source documents. [16, 18] The assumptions are as follows:

1. Targets are circles with aim points at the center.
2. The error in locating the center of the target will be distributed normally about the true center of the target with standard deviation σ_L = target location error.
3. The round impact points are also distributed normally about the aim point with a standard deviation σ_D independent of location error.
4. The probability that a given round impacts within a given small region of the target is small.
5. Personnel comprising the target are randomly distributed throughout the target area A_t and the individual round mean area of effectiveness MAE is small compared to A_t.

Utilizing these assumptions, the actual impact points are distributed normally about the target center with the standard deviation of each round

$$\sigma = \sqrt{\sigma_L^2 + \sigma_D^2} = 0.85 \text{ CEP}$$

The rounds are considered nearly independent and the coverage is nearly uniform. From this the expected fraction of casualties is

$f = 1 - \exp(-n \text{ MAE}/A_t)$

n = number of rounds expected to fall in the target area

n = N Pr where

N = total number of rounds fired

Pr = the probability that any round fired falls into the target area and is a function of the target radius R_t and σ

$$= 1 - \exp\left(- 1/2 \left(\sigma / R_t \right)^2 \right)$$

Substitute Pr and n into f, take the natural logarithms and

$$N = - \frac{A_t}{Pr\ MAE} \ln (1 - f_d) \text{ where}$$

f_d = fraction of casualties desired